REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*: 3/20/02

2. REPORT TYPE: Final Technical Report

3. DATES COVERED *(From - To)*: 01/01/97 - 12/31/01

4. TITLE AND SUBTITLE: Positron Plasmas in the Laboratory

5a. CONTRACT NUMBER:

5b. GRANT NUMBER: N00014-97-1-0366

5c. PROGRAM ELEMENT NUMBER:

5d. PROJECT NUMBER:

5e. TASK NUMBER:

5f. WORK UNIT NUMBER:

6. AUTHOR(S)

Clifford M. Surko

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

The Regents of the University of California
University of California, San Diego
La Jolla, CA 92093

8. PERFORMING ORGANIZATION REPORT NUMBER: Fin-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
Program Officer: Dr. Charles W. Roberson, Code 331
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S):

11. SPONSORING/MONITORING AGENCY REPORT NUMBER:

12. DISTRIBUTION AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

20020328 075

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This grant supported work to develop efficient methods to accumulate low-energy positrons in the laboratory and to use the resulting positron plasmas for a range of scientific and technological applications. Techniques for trapping and manipulating positrons were refined and expanded. A new generation of positron accumulator was designed and built. It functions up to specifications, confining 3×10^8 positrons at densities $\geq 10^7$ cm^{-3}. A new technique to create ultra-cold positron beams with these plasmas was used for new studies of the instabilities created when a cold electron beam is passed through a positron plasma. This cold beam technique has now been used for a wide range of novel positron scattering and annihilation experiments to study the interaction of low-energy positrons with atoms and molecules. A new high magnetic field, cryogenic positron storage trap was constructed and is being tested. Other accomplishments during the grant period include the development of a rotating electric field technique to radially compress positron plasmas. This, in turn, was enabled by the development of a method to cool the positrons with a polyatomic buffer gas. This cooling technique also provides new capabilities for the generation of cold positron beams operating at high repetition rates.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
				5	C. M. Surko
					19b. TELEPONE NUMBER *(Include area code)*: 858-534-6880

Final Technical Report
Positron Plasmas in the Laboratory
Office of Naval Research Award N00014-97-1-0366
(January 1, 1997 to December 31, 2001)

Clifford M. Surko
Department of Physics
University of California, San Diego
La Jolla, CA 92093-0319

Overview. This grant supported work to develop efficient methods to accumulate low-energy positrons and to use the resulting positron plasmas for a range of scientific and technological applications. The principal investigator and his collaborators developed an efficient method to accumulate and store low energy positrons. During this grant, these techniques for trapping and manipulating positrons were refined and expanded. A new generation of positron accumulator was designed and built. It functions up to specifications, confining 3 x 10^8 positrons at densities > 10^7 cm^{-3}. A new technique had recently been developed to create cold positron beams with these plasmas. This beam was used during the grant for studies of the instability created when a cold electron beam is passed through a positron plasma. This cold beam was also used for a wide range of novel positron scattering and annihilation experiments to study the interaction of low-energy positrons with atoms and molecules. A new high-field, cryogenic positron storage trap has been constructed and is now being tested with electrons. Other accomplishments include the development of a rotating electric field technique to radially compress positron plasmas. This technique was, in turn, enabled by the development of a new method to cool the positrons using a polyatomic buffer gas. This cooling technique also provides new capabilities for the creation of cold positron beams.

References to the work described below are indicated at the end of the corresponding paragraph. These references are listed (in chronological order) at the end of this report. The papers cited were either published or accepted for publication during the grant period.

New positron accumulator. Most of the design of the second-generation of positron accumulator described above was in place at the beginning of this grant. The design was completed, the apparatus built, and the accumulator was brought into operation during the grant period. The design was optimized to create a more compact and rugged device, with the capability of achieving rapid, UHV operation (i.e., within ~ 10 s) following positron accumulation using a buffer gas. Plasmas of 3 x 10^8 positrons can be accumulated in a few minutes in this device, with plasma densities > 10^7 cm^{-3} and improved radial profiles (i.e., ~ 0.7 cm, FWHM). The design of this device has been adapted for the positron source in an experiment at CERN in Geneva to form and trap cold antihydrogen atoms. The new positron accumulator has been the workhorse for all subsequent positron experiments conducted during the grant period. [1, 3, 9, 15, 23, 25]

Cold beam experiments. Immediately preceding this grant, we developed a new method to create cold positron and electron beams by carefully extracting the particles from a Malmberg-Penning trap. During the grant period we exploited this technique for a range of new experiments. We had previously studied the electron-beam positron-plasma instability. The new cold-beam formation technique allowed us to create much colder electron beams (i.e., as compared with those produced using conventional electron guns). Using this technique, we were able to study the growth rate of a transit-time instability (observed in short positron plasmas) over the entire region of positive growth (i.e., as a function of electron-beam energy). These results motivated a new theory of this instability by D.H.E. Dubin that accurately models the geometry of the experiment. Good, quantitative agreement between theory and experiment was achieved. The theoretical and experimental results were published last year in a paper in Physics of Plasmas [17]. While a multitude of theoretical papers have studied electron-positron plasmas (largely in the context of astrophysical plasmas), our work represents the first experiment on the electron-positron plasma system. [4, 6, 17, 24]

The cold positron beam also enabled many new positron atomic-physics experiments. A number of important results were obtained during the grant period. We invented a method to do positron scattering experiments that is specifically designed for use with a magnetized positron beam (i.e., in contrast to conventional atomic physics scattering experiments using electrostatic beams). We made the first studies of the excitation of vibrational modes in molecules by positrons (CF_4, CO_2, CO, CH_4 and H_2). We were able to make quantitative comparison with theory in a number of cases. We also made the first state-resolved measurements of the *electronic* excitation of atoms and molecules (Ar, N_2, and H_2) using positrons. In this case also, quantitative comparison was made with a number of theoretical predictions. In the case of H_2, we were able to distinguish between two competing theories. In the case of Ar, we were able to test whether positron impact can result in a spin flip in the target atom -- the answer is no in argon. A range of other scattering experiments were conducted, including total scattering cross section measurements and a search for electronic resonances. At the end of the grant period, work focused on developing techniques to go to very low values of positron energy, e.g., ≤ 100 meV. [2, 5, 7, 8, 11, 12, 14, 18- 22, 26]

Rotating-wall compression of positron plasmas and polyatomic buffer-gas cooling. In collaboration with R. G. Greaves, First Point Scientific, Inc. [FPSI], Agoura Hills CA, we developed a method to radially compress positron plasmas by the application of a rotating electric field. While this technique had been used previously for ion and electron plasmas, ours was the first experiment to compress positron plasmas. A new operating regime was discovered in which plasmas could be compressed by the application of a rotating electric field much faster than in previous experiments. The success of the experiment hinged on the development of a rapid method of rapid positron cooling using a suitably chosen polyatomic gas. This avoids the use of cyclotron cooling, which requires a high magnetic field and is, in many cases, a distinct disadvantage. The polyatomic gas cooling was also used to improve the duty cycle of the cold positron beam for atomic physics experiments. [13, 16]

Cryogenic, high magnetic field storage trap. During the grant period we designed and constructed a Penning-Malmberg positron trap that will operate in a 5 tesla magnetic field with electrodes cooled to 10 kelvin. This device, when fed with the high-efficiency buffer-gas positron accumulator, will make a nearly ideal source of cold, high-density positron plasmas. This device is designed to accumulate and store ultra-dense, cold positron plasmas (positron accumulation rates $\geq 10^{10}$/h; densities $n \geq 10^{10}$ cm^{-3}, and plasma temperatures ~10K). The magnet and vacuum system work flawlessly. The immediate task is bringing on line a number of subsystems. The electrical circuit for the rotating wall electrodes have been constructed and tested. A new computer system and a new hardware interface for the electrodes is in progress. The electrodes have been cooled to < 80 K, and a thermal link is now being improved to achieve the design specification of 10K. Testing the trap with electrons has begun. We are now designing the beam tube to connect this trap to the high-efficiency buffer-gas positron accumulator. Also in the design stage is a set of electrodes to "stuff" the positrons into the high magnetic field region. First operation of the new trap on positrons is anticipated in summer, 2002. This new cryogenic trap offers the possibility of being able to produce a new generation much colder positron beams (e.g., ~ 1 meV, FWHM), using the technique described above. [9]

Applications of positron beams. We continue a successful collaboration with R. G. Greaves (FPSI) on problems of mutual interest, improving positron trapping and positron beam technology. Specific problems include creating brighter positron beams using the rotating wall technique, creating electrostatic positron beams from trapped plasmas, creating giant pulses of positrons, and understanding molecular fragmentation occurring as a result of positron annihilation and positronium formation. [10, 24]

Training of scientific personnel. The grant provided partial support for the training of four graduate student researchers, five postdoctoral researchers, and an assistant researcher.

Publications. There were 26 publications during the grant period citing ONR support, which are listed below, including five Physical Review Letters, one Applied Physics Letter, one invited review article, and one book chapter.

1. Stored Positrons for Antihydrogen Production, C. M. Surko, R. G. Greaves, and M. Charlton, *Hyperfine Interactions* **109**, pp. 181-188 (1997).

2. Gamma-ray Spectra From Positron Annihilation on Atoms and Molecules, K. Iwata, R. G. Greaves, and C. M. Surko, *Phys. Rev. A* **55**, pp. 3586-3604(1997).

3. Antimatter Plasmas and Antihydrogen, R. G. Greaves and C. M. Surko, *Phys. Plasmas* **4**, pp. 1528-1543 (1997).

4. Creation of a Monoenergetic Pulsed Positron Beam, S. J. Gilbert, C. Kurz, R. G. Greaves, and C. M. Surko, *Appl. Phys. Lett.*, **70**, pp. 1944-1946 (1997).

5. Studies of Positron-Matter Interactions Using Stored Positrons in an Electrostatic Trap, K. Iwata, R. G. Greaves, C. Kurz, S. J. Gilbert, and C. M. Surko, *Positron Annihilation ICPA-11*, Y. C. Jean, M. Eldrup, D. M. Schrader, and R. N. West, eds. (Trans Tech Publications, Switzerland, 1977), pp. 223-227.

6. New Source of Ultra-cold Positron and Electron Beams, C. Kurz, S. J. Gilbert, R. G. Greaves and C. M. Surko, *J. Nuclear Instruments and Methods B*, 143, pp. 188-94 (1998).

7. Atomic and Molecular Physics Using Positrons in a Penning Trap, C. M. Surko, K. Iwata, C. Kurz, and S. J. Gilbert, in *Photonic, Electronic and Atomic Collisions,* F. Aumayr and H. P. Winter, eds. (World Scientific, Hong Kong, 1998), pp. 383-392.

8. Positron Scattering from Atoms and Molecules at Low Energies, S. J. Gilbert, R.G. Greaves, and C. M. Surko, *Phys. Rev. Lett.*, 82, 5032-35 (1999).

9. Progress in Creating Low-energy Positron Plasmas and Beams, C. M. Surko, S. J. Gilbert, and R. G. Greaves, *Non-neutral Plasma Physics III*, J. Bollinger, R. Spencer, and R. Davidson, eds. (American Institute of Physics, 1999), pp. 3 - 12.

10. Technological Applications of Trapped Positrons, R. G. Greaves, and C. M. Surko, *Non-neutral Plasma Physics III*, J. Bollinger, R. Spencer, and R. Davidson, eds. (American Institute of Physics, 1999), pp. 19 – 28.

11. Atomic and Molecular Physics Using Positron Accumulation Techniques -- Summary and a Look to the Future, C. M. Surko, R. G. Greaves, K. Iwata, and S. J. Gilbert, *Nuclear Instruments and Methods in Physics Research* **B 171**, 2 - 16 (2000).

12. Low-energy Positron Scattering from Atoms and Molecules using Positron Accumulation Techniques, S. J. Gilbert, J. Sullivan, R. G. Greaves, and C. M. Surko, *Nuclear Instruments and Methods in Physics Research* **B 171**, 81 - 95 (2000).

13. Inward Transport and Compression of a Positron Plasma by a Rotating Electric Field, R. G. Greaves and C. M. Surko, *Phys. Rev. Lett.*, **85**, 1883 (2000).

14. Excitation of Molecular Vibrations by Positron Impact, J. P. Sullivan, S. J. Gilbert and C. M. Surko, *Phys. Rev. Lett.*, **86**, 1494-97 (2001).

15. Positron Traps and Trap-based Beams: Status and Future Prospects, C. M. Surko, *Mat. Sci. Forum* , **363-365**, pp. 624-628, 2001.

16. Radial Compression and Inward Transport of Positron Plasmas Using a Rotating Electric Field, R. G. Greaves, and C.M. Surko, *Phys. Plasmas*, **8**, 1879-85, 2001.

17. An Electron-Positron Beam-Plasma Instability, S.J. Gilbert, D. H. E. Dubin, R. G. Greaves, and C.M. Surko, *Phys. Plasmas*, **8**, 4982-94 (2001).

18. Excitation of Electronic States of Ar, H, and N by Positron Impact, J. P. Sullivan, J. P. Marler, S. J. Gilbert, S. J. Buckman, and C. M. Surko, *Phys. Rev. Lett.*, **87**, 0733203 (2001), 4 pages.

19. Search for Resonances in the Scattering of Low-energy Positrons from Atoms and Molecules, J. P. Sullivan, S. J. Gilbert, S. J. Buckman, and C. M. Surko, *J. Phys.* **B34**, L 467 (2001), 8 pages.

20. Vibrational-resonance Enhancement of Positron Annihilation in Molecules, S. J. Gilbert, L. D. Barnes, J. P. Sullivan and C. M. Surko, *Phys. Rev. Lett.*, **88**, 043201 (2002) 4 pages.

21. Atomic and Molecular Physics Using Positron Traps and Trap-Based Beams, C. M. Surko, in *New Directions in Antimatter Chemistry and Physics*, (Kluwer Scientific Publishers, the Netherlands, 2001), pp. 345-365.

22. Low-Energy Positron-Matter Interactions Using Trap-Based Beams, S. J. Gilbert, J. P. Sullivan, J. P. Marler, L. D. Barnes, P. Schmidt, S. J. Buckman and C. M. Surko, F. Anderegg, L. Schweikhard, C. F. Driscoll, editors, *Non-neutral Plasma Physics IV*, (AIP Conf. Proceedings #606, Melville, NY, 2001), pp. 24-34.

23. Practical Limits on Positron Accumulation and the Creation of Electron-Positron Plasmas, R. G. Greaves and C. M. Surko, F. Anderegg, L. Schweikhard, C. F. Driscoll, editors, *Non-neutral Plasma Physics IV*, (AIP Conf. Proceedings #606, Melville, NY, 2001), pp. 10-23.

24. Trap-Based Positron Beams, R. G. Greaves, S. J. Gilbert, and C. M. Surko, Appl. Surface Sci. 7876, 2002.

25. Positron Trapping and the Creation of High-Quality Trap-Based Positron Beams, R. G. Greaves and C. M. Surko, Nuclear Instrum.and Meth. for *Physics Res.* **B.**, in press.

26. Low Energy Positron Scattering and Annihilation Studies Using a High Resolution Trap-Based Beam, J. P. Sullivan, S.-J. Gilbert, J. P. Marler, L. D. Barnes, S. J. Buckman, and C. M. Surko, Nuclear Instrum. and Meth. for *Physics Res.* **B.**, in press.